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Sustainable energy development strategies: implications of energy demand management and renewable energy in Thailand

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Abstract

A brief review of energy use patterns in three economic sectors; namely, residential, industrial and transport sectors is provided in this paper. The transport sector is the largest energy-consuming sector in Thailand, followed by the industrial and residential sectors, respectively. In order to reduce both imported energy and environmental emissions, energy conservation programs would be implemented. This paper forecasts the growth in energy demand and corresponding emissions to the year 2020 for those three sectors by using a model based on the end-use approach. The energy savings from the energy conservation strategies, such as energy efficiency improvement and energy demand management, are assessed and also the implications on electricity generation expansion planning are examined. The integrated resource planning (IRP) model is used to find the least-cost electricity generation expansion plans. Energy conservation options, including energy efficiency improvement programs, are introduced in the residential and industrial sectors. Public transportation and engine technology improvements are introduced in the transport sector. The effects of energy conservation options are analyzed using a scenario-based approach. The results of analysis reveal that the improvement of public transportation can reduce future energy requirements and CO_2 emissions in 2020 by 635 thousand ton of oil equivalent (toe) and 2024 thousand ton of CO_2 equivalent, respectively. If all options are simultaneously implemented, the potential of energy savings and CO_2 mitigation in 2020 are estimated to be 1240 thousand toe and 3622 thousand ton of CO_2 equivalent, respectively.

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Contents

1. Introduction

Almost 50% of the total commercial energy supply in Thailand has been imported. In 2000, total energy imported was 39 730 thousand toe, an increase of 2.0% over the previous year [1]. The three economic sectors, namely, transport, industrial and residential sectors are the most energy-consuming sectors in Thailand. In 2000, the

transport sector consumed 18 652 thousand toe, accounting for 38.6% of total final energy consumption, followed by the industrial and residential sectors, accounting for 34.6% and 15.4% of final energy consumption, respectively. In order to reduce not only the imported energy but also the environmental emissions, these three sectors would be the main targets for implementing energy conservation programs.

Due to the shortage of fossil fuel resources and the awareness of the air pollution problem, which is produced by the use of fossil fuel, the Thai government has tried to solve these problems. The most popular conservation activity to reduce energy consumption is known as the demand-side management or DSM. The DSM is also viewed as one of the most cost-effective ways to reduce greenhouse gases such as CO_2 [2]. Firstly, the DSM programs in Thailand were aimed at reducing electricity consumption of residential and commercial consumers. The program involves a campaign to promote efficient electric appliances such as fluorescent lamps, refrigerators and air conditioners. In recent years, efficient electric ballast and the high efficiency electric motors could be in the campaign. However, the efficient ballasts and efficient electric motors programs are not successful due to their high capital cost. Presently, a successful campaign is the labeling campaign for efficient refrigerators and air conditioners. Also, the efficient electric fans are already involved in the labeling campaign in 2002.

In addition, a DSM option has been introduced in the transport sector. As the number of passenger cars (or sedan cars) has continuously increased, the traffic in the Bangkok Metropolitan area has become heavily congested. The passenger cars in Bangkok accounted for more than 50% of total passenger cars registered in 2000 [3]. In recent years, much attention has been given to congestion management strategies that can be used to alleviate traffic problems and also reduce energy consumption, especially in the Bangkok Metropolitan area. Transport Demand Management (TDM) strategies have long been contemplated as one of the approaches to solving congestion problems. Since the supply of transportation infrastructure alone cannot solve congestion problems, the TDM has grown in popularity and acceptance around the world. The TDM measures can be broadly classified into four approaches; namely, increasing vehicle occupancy, peak period diversion, route diversion to a less congested network and reducing overall demand in the system [4]. Therefore, in order to promote and to stimulate the awareness of energy conservation in the transport sector, many advisory spots and energy conservation activities have been conducted, such as car pool and car free day campaigns. Those activities aimed at increasing the number of passengers per vehicle and reducing overall energy demand of the system. However, to achieve the successful implementation of TDM strategies, it is important to determine a priori the acceptability of specific strategies. The results obtained from the study of Bhattacharjee et al. [5] indicate that the commuters accepted public transportation improvement as the most desirable and effective policy. The introduction of mass rapid rail transit was rated as the best measure to combat Bangkok traffic problems, followed by the introduction of staff buses as a shared-ride strategy.

Against this background, the long-range energy alternatives planning (LEAP) model is used to analyze energy demand and environmental emissions under alterna-

tive strategies in three main economic sectors, namely, transport, industrial and residential. In order to evaluate the potential of energy conservation and emission reduction, especially CO_2 emission, two scenarios: business-as-usual (BAU) and alternative scenarios, are assessed. In the alternative scenarios, energy efficiency improvement in selected appliances is introduced in the residential and industrial sectors. Two strategies: public transportation improvement and engine technology improvement are introduced in the transport sector. The period of study starts in 2003 and ends in 2020, with 2000 taken as the base year. Additionally, this paper also examines the impact of these strategies on the power generation expansion planning, because the change in electricity demand directly affects the selection of generation technologies in the electricity generation plan. The integrated resource planning (IRP) model, developed by Shrestha et al. [6], is used to determine the least-cost electricity generation expansion plan.

2. Energy use pattern in the transport, industrial and residential sectors

The energy requirement can be broadly divided into two categories: electricity and non-electricity. The proportion of each energy requirement depends on the activity purposes in each sector.

In the transport sector, most of the energy demand in 2000 was for petroleum products, comprising diesel 53.4%, gasoline 26.6%, jet fuel 15.3%, fuel oil 3.7%, and liquefied petroleum gas (LPG) 1.0%, whereas a small fraction of electricity was initially used by sky trains [1]. The road transport takes the highest proportion of 80% of total energy consumption. For the vehicles registered under the Motor Vehicle Act, motorcycles accounted for as much as 66.31%, while passenger cars (sedan car) plus microbuses and passenger pickups and vans and pickups altogether accounted for another 28% [3].

The majority of energy consumed in the industrial sector is based on non-electricity, comprising renewable energy, petroleum products, coal and its products, and natural gas. In 2000, the share of non-electricity requirement was 80.0% of the sectors' final energy demand [1]. The major purpose of non-electricity utilization, mainly used in boilers and furnaces, is the thermal purpose. Although electricity consumption has not been the largest proportion of energy consumed in this sector, its share has been increasing rapidly. The share of electricity consumption accounted for 20.0% of total energy demand in this sector. The electric motor is the major electric equipment used in the industrial process.

In the residential sector, the proportion of electricity requirement was 22.3% of total energy consumption and the remaining proportion of non-electricity demand was 77.7% in 2000 [1]. The electricity demand in this sector has been in electric devices, especially air conditioners, refrigerators and lighting. The non-electricity demand has been primarily in cooking devices such as charcoal stove, wood stove and LPG cooking stove. The non-electricity energy in this sector comprises renewable energy such as wood, charcoal, and petroleum products such as LPG.

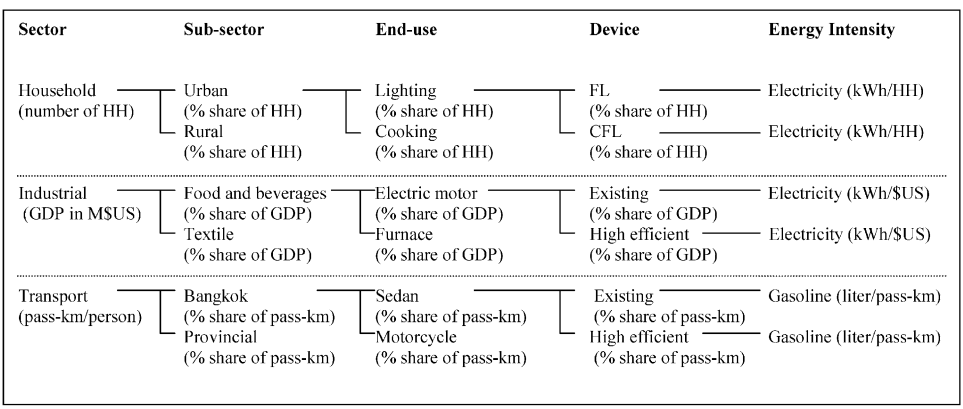
3. Framework of energy demand model

3.1. The model framework

The LEAP model has been developed by the Stockholm Environment Institute-Boston (SEI-B) and used to evaluate energy development policies [7]. The central concept of LEAP is an end-use driven scenario analysis. Additionally, the model includes the technology and environmental database (TED) to estimate environmental emissions of the energy utilization. In this study, the current energy situation is created in the starting year, and a base scenario can be developed assuming a contribution of current trends. This BAU scenario is called the base case. Then, other policy scenarios with alternative assumptions are developed as an alternative case. The LEAP model emphasizes the detailed evaluation of specific energy problems within the context of integrated energy and environmental planning for each scenario or combination of scenarios.

The LEAP framework is disaggregated in a hierarchical tree structure of four levels: sector, sub-sector, end-use, and device (see Fig. 1). The model contains two main modules: the energy demand module and the TED module. In the energy demand module, the energy intensity values along with the type of fuel used in each device are required to estimate the energy requirements at sector, sub-sector and end-use level. The emission factors of different pollutants in the TED module are linked to the device level to appraise the environmental emission from the energy utilization during the planning horizon.

The LEAP model requires data for at least the base year and any of the future years. Then, using the function such as interpolation or extrapolation or the growth rate method, the future energy demand and emissions are estimated for the other years. However, in this study some parameters, which will be described below, are prepared and then input to the model. Taking into account the projected parameters



Notes: HH stands for household. FL stands for fluorescent lamp. CFL stands for compact fluorescent lamp.

Fig. 1. Example of tree structure in the energy demand module of LEAP model.

in the LEAP model, the energy demand and their emissions are also evaluated. In this study, the emission factors are based on values recommended by the Intergovernmental Panel on Climate Change [8].

3.2. Model of energy demand

The model of energy demand in each sector is formulated and disaggregated based on the format of the LEAP model. The historical data are the secondary data collected from several reports of the government and non-government agencies such as the National Economic and Social Development Board (NESDB), Department of Local Administration (DOLA), National Statistical Office (NSO), Bangkok Mass Transit System Public Company Limited (BTS), etc. and other research.

3.2.1. Transport sector

In the transport sector, only the road transport is considered due to its high proportion in total consumed energy in the transport sector. The energy demand can be estimated by using the volume of traffic in terms of vehicle kilometer. The number of vehicles should be projected and then multiplied with the average distance per year to appraise the vehicle kilometers per year. The energy demand in road transportation is formulated as a function of the number of vehicles, average distance, proportion of vehicle type and fuel economy or fuel efficiency of vehicle. However, in the LEAP framework total passenger-travel demand is expressed in terms of passenger-kilometers. So, total travel demand in the sector level is estimated as follows:

$$\mathrm{TD}_t = \sum V_{i,t} \times D_i \times \mathrm{LF}_i \tag{1}$$

where TD_t denotes the total travel demand in year t expressed in passenger-kilometers (pass-km), $V_{i,t}$ denotes the number of vehicles i registered in year t, D_i denotes the average distance of vehicle i (km) and LF_i denotes the load factor of vehicle i or the average number of occupants (passenger/vehicle).

Generally, the number of population per vehicle tends to decrease when a country develops. In order to estimate the number of vehicles, from the person-per-vehicle point of view, there should be a lower limit of car ownership to be incorporated in the estimated number of vehicles [9]. The estimation can be done with the log-limit equation where the limit is incorporated in the GDP and population. The number of vehicles can be estimated by the following equation:

$$V_{i,t} = \mathrm{e}^{(a_i + b_i \times \mathrm{GDP}_t + c_i \times \mathrm{Pop}_t)} + \mathrm{LV}_i \tag{2}$$

where LV_i denotes the lower limit of vehicle type i, and a_i, b_i, and c_i denote the coefficients in the model of vehicle i. Lower limits of each vehicle used in this study and comparison of model-based forecast and actual number of registered vehicles in 2000 are presented in Tables 1 and 2, respectively. The travel demand for road transportation is estimated based on Eqs. (1) and (2), as shown in Table 3.

In sub-sector and end-use levels, the shares of total passenger travel demand by different areas and different vehicles are estimated based on Eq. (1). Each vehicle

Table 1
Lower limits of persons per vehicle

Vehicle types	Actual no. of persons per vehicle in 2000[a]			Other studies		This study		
	Whole	Bangkok	Province	A[b]	B[c]	Whole	Bangkok	Province
1. Passenger car	29	5	65	3	3	3	3	3
2. Microbus and pickup	105	15	217	3	100	100	10	100
3. Van and pickup	19	8	23	3	3	3	3	3
4. Motortricycle	13 225	6279	14 777	–	–	10 000	5000	10 000
5. Urban taxi	931	88	26 409	–	50	50	50	50
6. Fixed route taxi	7048	694	94 930	–	–	600	600	600
7. Motortricycle taxi	1310	767	1411	–	–	1000	700	1000
8. Motorcycle	4	3	5	3	3	3	3	3
9. Fixed route bus	845	369	971	200	400	400	350	400
10. Bus for hire	3301	816	4769	200	1000	1000	200	1000
11. Private bus	6938	1500	10 953	200	8000	1000	1000	8000
12. Non-fixed route truck	741	140	1307	20	200	100	100	200
13. Private truck	109	71	115	20	100	100	50	100
14. Tractor	556	277	619	50	–	500	100	550
15. Small rural bus	2910	0	2643	300	–	–	–	1000
16. Others	617	664	619	–	–	500	400	400

[a] Actual number of population per vehicle is obtained from [3].
[b] Study A is obtained from [9].
[c] Study B is obtained from [10].

Table 2
Comparison of model-based forecast and actual number of registered vehicles in 2000

Vehicle types	Bangkok Metropolitan		Provincial		Whole Kingdom	
	Actual	Forecast	Actual	Forecast	Actual	Forecast
1. Passenger car	1 240 985	1 351 213	870 178	807 968	2 111 163	2 159 181
2. Microbus and pickup	295 527	357 465	258 715	216 231	554 242	573 696
3. Van and pickup	737 476	774 165	2 472 049	2 463 093	3 209 525	3 237 258
4. Motortricycle	1076	893	3803	3116	4879	4009
5. Urban taxi	64 321	65 576	2128	2156	66 449	67 732
6. Fixed route taxi	8187	8195	592	667	8779	8862
7. Motortricycle taxi	7403	7401	39 824	39 755	47 227	47 155
8. Motorcycle	1 964 850	1 825 945	11 851 710	11 729 901	13 816 560	13 555 846
9. Fixed route bus	15 379	14 601	57 876	56 694	73 255	71 295
10. Bus for hire	6961	7268	11 785	12 322	18 746	19 590
11. Private bus	3788	3664	5131	4142	8919	7745
12. Non-fixed route truck	40 442	37 402	43 011	43 086	83 453	83 453
13. Private truck	79 721	75 857	489 346	488 508	569 067	564 365
14. Tractor	20 518	20 235	90 784	91 685	111 302	111 920
15. Small rural bus	–	–	21 267	21 890	21 267	21 890
16. Others	8553	8513	90 741	88 619	99 294	97 132

Table 3
Estimated travel demand for road transportation

Vehicle types	Estimated travel demand (10^6 passenger-kilometer)					
	2000		2010		2020	
	BKK	Province	BKK	Province	BKK	Province
1. Passenger car	19 402	12 244	28 528	59 596	30 980	162 904
2. Microbus and pickup	6190	5419	9542	4342	11 137	4224
3. Van and pickup	12 750	42 740	28 100	119	33 784	247 911
4. Motortricycle	16	57	13	89	12	101
5. Urban taxi	3961	131	6065	78	7085	45
6. Fixed route taxi	158	11	140	15	110	30
7. Motortricycle taxi	244	560	241	452	235	278
8. Motorcycle	11 057	66 695	10 947	105 733	11 262	125 186
9. Fixed route bus	972	2430	999	3122	1049	4000
10. Bus for hire	383	656	581	1098	747	1672
11. Private bus	125	161	74	219	33	262
12. Non-fixed route truck	1258	2806	1621	5631	1821	10 170
13. Private truck	4877	29 936	5768	35 404	6317	38 770
14. Tractor	592	2620	966	2907	1 341	2 911
15. Small rural bus	–	893	–	673	–	449
16. Others	80	852	118	510	136	223

is disaggregated into existing technologies and alternative technologies or fuels. The energy intensities of vehicle technologies under device level are calculated based on fuel economy and occupancy, and expressed in terms of liters per passenger-kilometer

$$\mathrm{EIV}_i = \frac{1}{(\mathrm{FE}_i \times \mathrm{LF}_i)} \tag{3}$$

where EIV_i denotes energy intensity of vehicle i (l/pass-km) and FE_i denotes fuel economy of vehicle i expressed in vehicle-kilometers per liter (veh-km/l). The energy intensity of vehicle type is estimated as presented in Table 4.

In 2000, the Bangkok Mass Transit System (BTS) or the sky train has been operated. Therefore, the electricity demand for this transport mode is considered. The estimation of transport demand is based on the load factor, average distance and operating hours in 2000 [11].

3.2.2. Industrial sector

In this study, the industrial sector can be broadly classified into nine manufacturing sub-sectors, including food and beverages, textile, wood and furniture, paper, chemical, non-metalic, basic metal, fabricated metal, and others (unspecified). The energy demand projection in the industrial sector is formulated as a function of gross domestic product (GDP), proportion of utilized energy, device efficiency and useful energy intensity.

In sector and sub-sector levels, the historical data of GDP are taken from the NESDB and used to project the future GDP by using the average annual growth rate of 3%. The proportions of GDP in the industrial sub-sectors are assumed to be constant during time horizon. The proportions of energy utilized in end-use and device levels are derived from the energy consumption in 2000 [1] and are also assumed to be constant during the planning period, as presented in Table 5. The average efficiencies of industrial equipment are taken from the energy audits reports of King Mongkut's University of Thonburi (KMUTT). However, it is too difficult to classify types of devices with a specific energy because of the variety of devices and also the limitation of data in the industrial sector. So, it is assumed that each type of energy in each manufacturing sub-sector is used in a specific device. The useful energy intensity is estimated by the following equation:

$$\mathrm{UEI}_j = \sum_t \frac{(\mathrm{EnU}_{i,j} \times \eta_{i,j})}{\mathrm{GDP}_j} \tag{4}$$

where UEI_j denotes the energy intensity in industrial sub-sector j (ktoe/10^6 Baht), $\mathrm{EnU}_{i,j}$ denotes the energy type i utilized in industrial sub-sector j (ktoe), $\eta_{i,j}$ denotes the efficiency of equipment using fuel type i utilized in industrial sub-sector j, and GDP_j denotes the gross domestic products of industrial sub-sector j (10^6 Baht). The average useful energy intensity in each sub-sector is presented in Table 6.

Table 4
Fuel economy of the automotive technologies divided by types of fuel

Types of vehicle	Average fuel economy (l/km)					
	Bangkok Metropolitan area			Provincial area		
	Gasoline	Diesel	LPG	Gasoline	Diesel	LPG
Passenger car	0.085690	0.080257	–	0.087336	0.081235	0.100000
Microbus and passenger pickup	0.081235	0.072202	–	0.083195	0.082440	–
Van and pickup	0.080515	0.073260	–	0.087413	0.082305	0.100000
Motortricycle	0.083333	–	0.071429	0.083333	–	0.071429
Urban taxi	0.085690	–	0.085985	0.085690	–	0.085985
Fixed routed taxi	0.076923	–	–	0.076923	0.066667	–
Motortricycle taxi	0.080000	–	0.087184	0.056850	–	0.087184
Motorcycle	0.040750	–	–	0.047551	–	–
Fixed route bus	–	0.091659	–	–	0.103199	–
Bus for hire	–	0.095877	–	–	0.095877	–
Private bus	–	0.095420	–	–	0.095420	–
Non-fixed route truck	–	0.108696	–	–	0.108696	–
Private truck	–	0.125628	–	–	0.125628	–
Tractor	–	0.136612	–	–	0.136612	–
Small rural bus	–	–	–	–	0.103199	–
Others	–	0.063492	–	–	0.063492	–

Source: Ref. [12].

Table 5
Proportions of energy utilization in industrial sub-sectors

Fuel types	Proportion of energy utilization (%)								
	Food	Textile	Wood	Paper	Chemical	Non-metalic	Basic metal	Fabricated metal	Others
NG[a]	1.00	–	–	–	18.93	18.17	–	21.41	–
LPG[b]	0.82	1.00	0.86	3.20	3.52	0.76	3.36	2.49	6.01
Kerosene	0.01	0.07	0.02	0.04	0.07	0.05	0.09	0.40	1.32
Gasoline	0.03	0.21	0.24	0.11	0.11	0.18	0.07	0.37	2.47
Diesel	2.60	1.25	10.61	2.48	2.59	1.32	4.06	1.74	13.28
Fuel oil	10.16	42.24	10.85	29.54	12.26	7.49	26.07	6.60	70.35
Electric	10.71	48.38	69.35	18.54	27.59	10.47	41.10	66.99	2.00
Imported coal	–	–	–	–	25.33	24.66	9.11	–	–
Coke	–	–	–	–	–	–	16.14	–	–
Anthracite	–	–	–	–	5.09	–	–	–	–
Lignite	0.93	6.85	–	46.09	–	32.56	–	–	4.57
Fuel wood	9.12	–	8.07	–	4.51	3.97	–	–	–
Rice husk	12.80	–	–	–	–	0.37	–	–	–
Bagasse	51.82	–	–	–	–	–	–	–	–

Source: Ref. [10].
[a] NG stands for natural gas.
[b] LPG stands for liquefied petroleum gas.

Table 6
Average useful energy intensities in industrial sub-sectors

Sub-sector	Average useful energy intensity (ktoe/10^6 Baht)
Food and beverages	0.0213388
Textile	0.0052836
Wood and furniture	0.0100809
Paper	0.0185502
Chemical	0.0094627
Non-metalic	0.0216113
Basic metal	0.0338194
Fabricated metal	0.0225538
Others	0.0155091

3.2.3. Residential sector

Based on the LEAP framework and the tree structure in the demand module in Fig. 1, the projection of the number of households over time horizon is formulated as a function of the population and size of households as follows:

$$H_t = \frac{P_t}{S_t} \tag{5}$$

where H_t denotes the number of households in year t, S_t denotes the size of households in year t, and P_t denotes the number of population in year t. The household sizes of the projected population are estimated by using the log-limit model [10]. The lower limit of household sizes applied in this study is three persons per household. The projection of number of households is presented in Table 7.

In sub-sector level, the proportion of the number of households is separated into two major areas: urban (Bangkok Metropolitan) and provincial, and estimated by using Eq. (5).

The proportion of end-use devices is disaggregated into existing appliances and high efficiency appliances, which are either in use or are likely to be introduced in the future. The energy intensity of each appliance can be formulated as a function of number of appliances, capacity of appliances and average usage hours. The average number of appliances per household and usage hours per day are obtained from the statistical data and reports of the Department of Alternative Energy Development and Efficiency (DEDE), former named the "Department of Energy Development and Promotion (DEDP)" [13]. The average capacity of conventional and high efficiency appliances is taken from the public documents of the DEDE and market survey. The following equation is used to estimate the average energy intensity of each end-use appliance

$$\mathrm{EI}_i = \mathrm{hr}_i \cdot \mathrm{Cap}_i \cdot \mathrm{No}_i \tag{6}$$

where EI_i denotes the energy intensity of appliance i (kWh/year·HH), hr_i denotes the usage hours per year of end-use device i (h/year), Cap_i denotes the average capacity of end-use device i (kW), No_i denotes the average number of end-use device

Table 7
The number of projected households in each area

Year	Whole Kingdom	Bangkok Metropolitan				Municipal area		Rural area	
		Inner		Outer		Number of households	%	Number of households	%
		Number of households	%	Number of households	%				
2000[a]	16 515 322	1 516 503	9.18	1 393 477	8.11	3 144 174	19.04	10 462 168	63.34
2000[b]	16 644 347	1 497 289	9.00	1 411 856	8.48	3 169 084	19.04	10 566 118	63.48
2005	18 772 123	1 577 693	8.40	1 484 572	7.91	3 934 699	20.96	11 775 159	62.73
2010	20 409 553	1 617 235	7.92	1 627 772	7.98	4 710 169	23.08	12 454 377	61.02
2015	22 476 755	1 646 505	7.32	1 802 086	8.02	5 711 386	25.41	13 316 778	59.25
2020	23 493 257	1 669 754	7.11	2 006 319	8.54	6 572 885	27.98	13 244 298	56.37

[a] Actual number of households in 2000.
[b] Predicted number of households in 2000.

i per household (unit/HH), and HH denotes the household. The average intensity of end-use appliances is presented in Table 8.

3.3. Scenario construction and assumption used in this study

The LEAP model is implemented in three sectors: residential, industrial and transport sectors to illustrate the effect of alternative strategies on energy utilization and emissions. The BAU scenario is constructed based on the current trends in each sector. In the alternative scenarios, one scenario is conducted in the residential and industrial sectors and two scenarios are conducted in the transport sector.

3.3.1. Business-as-usual scenario

In the BAU scenario, the current trends of parameters in each sector are assumed to be increasing continuously, as described in the previous section. In the transport sector, the estimated travel demand based on the number of vehicles and occupancies, and average distances are presented in Table 3. The average fuel economy of each vehicle type is given in Table 4. In the industrial sector, the proportion of energy utilization in industrial sub-sectors and average useful energy intensities are shown in Tables 5 and 6. In the residential sector, the projected number of households and average energy intensities of appliances are presented in Tables 7 and 8. In the BAU scenario, the present efficiency of any appliances and technologies, and the pattern of energy utilization for different appliances and technologies are unchanged in the future. The ongoing projects are not implemented. In addition, the environmental emissions are also evaluated using TED of the LEAP model (see Table 9).

3.3.2. Alternative scenarios

3.3.2.1. Energy efficiency improvement in the residential and industrial sectors (EEI) scenario This scenario considers the replacement of low efficiency appliances with the high efficiency ones including both non-electric and electric appliances. For non-electric appliances, the conventional wood, charcoal, and LPG stoves are replaced by the high efficiency appliances with the same replacement rate of 20% of the additional appliances in each year. The non-electric appliances are considered only in the residential sector. For electric appliances, three types of efficient appliance programs in the residential sector are considered; namely, refrigerators, air conditioners and electric fans. The conventional refrigerator, air conditioner and electric fan are replaced by high efficiency ones with the replacement rate of 50% of the additional appliances in each year. In addition, one type of efficient appliance; electric motors, is considered in the industrial sector. The motors used in the industrial sector can be divided mainly into five groups corresponding to their capacity; namely, less than 5 hp, 5–20 hp, 20–50 hp, 50–125 hp, and more than 125 hp. The technical data for conventional and energy efficient motors (EEMs), including energy efficiency and annual operating hours, are based on Shrestha et al. [14] and NEPO [15]. The replacement rate of the high efficiency motor is based on the saving target of the DSM plan. The remaining data is the same as in the BAU scenario.

Table 8
Energy intensity of the appliances used in the residential sector

Type of appliance	Bangkok Metropolitan		Municipal area	Rural area
	Inner	Outer		
I. Non-electricity appliance[a]				
1.1 Wood stove	0	0.04089	0.15336	0.53676
1.2 Charcoal stove	0	0.10098	0.40392	0.50490
1.3 LPG stove	0.05364	0.08046	0.13410	0.07152
	0.05191[c]	0.07787[c]	0.12978[c]	0.06922[c]
II. Electricity appliance[b]				
2.1 Electric cooking stove	192.00	192.00	144.00	144.00
2.2 Rice cooker	106.20	106.20	212.40	212.40
2.3 Incandescent lamp	34.56	34.56	34.56	34.56
2.4 Fluorescent lamp	272.16	272.16	105.84	90.72
2.5 Compact fluorescent lamp	5.76	5.76	5.76	5.76
2.6 Refrigerator	311.11	311.11	311.11	311.11
	260.14[c]	260.14[c]	260.14[c]	260.14[c]
2.7 Air conditioner	3999.24	2488.42	833.18	464.20
	3423.17[c]	2129.97[c]	713.16[c]	397.33[c]
2.8 Fan	414.14	376.49	301.19	250.99
	392.04[c]	356.40[c]	285.12[c]	237.60[c]
2.9 Iron	144.00	144.00	96.00	96.00
2.10 Clothes washer	113.47	113.47	56.74	37.82
2.11 Water heater	462.00	462.00	180.00	180.00
2.12 VDO	3.60	3.60	2.16	2.16
2.13 Television	84.35	84.35	76.68	76.68
2.14 Radio	5.94	5.94	10.80	10.80

[a] Unit of energy intensity is toe/household year.
[b] Unit of energy intensity is kWh/household year.
[c] Figures are the average energy intensity of efficient appliances.

Table 9
Emission factors used in the LEAP model

Sector/appliances or fuel types	Emission factors[a] (kg/TJ energy consumed)						
	CO_2[b]	CO	CH_4	NO_x	N_2O	SO_2	TSP[c]
Residential							
–Wood stove	92.15	4402	261	6.1	–	–	68.70
–Charcoal stove	100.10	7570	334.90	10.0	–	–	179.50
–LPG cooking stove	67.30	325.7	1.09	3.21	–	–	11.20
Industrial							
–Natural gas	55.78	30	5	150	0.1	–	–
–LPG	72.92	10	2	200	0.6	0.068	–
–Kerosene	69.94	241.34	132.51	18.64	0.59	5.29	7.93
–Gasoline	68.56	27 000	4	1100	2.00	–	–
–Diesel	73.27	370	4	1100	30	–	–
–Fuel oil	72.55	10	2	200	0.6	994.26	–
–Lignite	92.64	150	10	300	1.4	884.06	–
Transport							
–Passenger car (gasoline)	68.65	1000	7	120	20	–	–
–Passenger car (diesel)	73.27	300	2	300	4	–	–
–Microbus (gasoline)	68.56	1000	7	120	20	–	–
–Microbus and pickup (diesel)	73.27	300	2	300	4	–	–
–Motortricycle (gasoline)	68.56	13 000	100	60	1	–	–
–Motortricycle (LPG)	1325	1450	30	380	–	–	–
–Motorcycle (gasoline)	68.56	12 000	100	200	1	–	–
–Bus (diesel)	73.27	1000	5	800	0.6	184.44	–
–Truck (diesel)	73.27	176	2	159	5.0	–	–
–Tractor (diesel)	73.27	357	4	567	2	–	–
–Other (diesel)	73.27	1000	5	800	0.6	184.44	–

Source: Ref. [7].

[a] Emission factors are based on the IPCC (Intergovernmental Panel on Climate Change) figures.

[b] Unit in ton/TJ energy consumed.

[c] TSP stands for total suspended particulate.

3.3.2.2. Public transportation improvement (PTI) scenario This scenario considers the public transportation system, especially the Mass Rapid Transit (MRT) and the extension of BTS. According to the master plan of Mass Rapid Transit Authority (MRTA), the first phase of the MRT project will be operated in 2003 with an average distance of 14 km. The total distance of the whole project is approximately 80.4 km, which will be completed in 2017 [16]. In addition, the extension project of BTS has been already approved. The total distance of the extended project is approximately 20 km. There are four assumptions taken into account in this scenario based on the plan of the MRTA. Firstly, the working time starts at 5:00 am and ends at 12:00 pm. Secondly, the commissioning schedule of the MRT project will be operated on time of the plan. Thirdly, the number of passengers is based on the MRTA's study. Finally, the extended project of BTS will be operational in 2007.

3.3.2.3. Fuel economy improvement (FEI) scenario This scenario considers the improved engine technologies that would reduce fuel requirement. In recent years, the efficiency of the automotive technologies in terms of fuel requirement per vehicle kilometer has been improved, especially the efficiency of passenger cars and passenger pickups. Two assumptions are taken into consideration in this scenario: (1) the proportion of the efficient passenger cars increases annually by 1% of the additional passenger cars in each year, and (2) the fuel economy of conventional and efficient automotive technologies is based on the study of King Mongkut's Institute of Technology Thonburi [12], as given in Table 4.

4. Electricity generation expansion planning

4.1. Framework of the IRP model

The electricity generation expansion planning in this study is based on the least-cost power expansion planning analysis. The IRP model is applied to determine the least-cost electricity generation expansion plans (see [6] for details of the formulation of the model). The objective function of the IRP model is the total cost including capacity cost of candidate power plants, fuel-cost, and also operating and maintenance costs of existing and candidate power plants. The emissions of CO_2, SO_2 and NO_x are automatically calculated based on the least-cost fuel requirement as determined by the IRP model by using the emission factors provided by the IPCC [8]. The IRP provides a wider choice of resources to meet the forecasted demand at a least-cost manner resulting in a lower emission level.

4.2. Input data and assumptions

In this analysis, the planning period starts in 2003 and ends in 2020, with 2000 taken as the base year. The data on existing committed and candidate power plants, annual peak demand, load profile and other related data are based on the Power

Development Plan [17] provided by the Electricity Generating Authority of Thailand (EGAT).

In 2000, total installed generating capacity was 18 951 MW, including 2886 MW of hydro power plants, 6493 MW of thermal power plants, 5075 MW of combined cycle power plants, 662 MW of gas turbine and diesel engine power plants, and 3842 MW purchased from other power suppliers [17]. The annual peak demand is obtained from the load forecast of EGAT, which supports information in the period of 2003–2011. The trend of the load is used to forecast the load from 2012–2020 at a constant load factor of 0.723 [17]. The system load is expected to increase from 18 399 MW in 2003 to 44 679 MW in 2020.

The candidate thermal plants can be classified into two categories: (1) conventional plants including coal- and oil-fired steam plants, gas-based combined-cycle plants, and diesel gas-turbine plants, and (2) renewable-based plants including biomass-based plants and solar power plants. The technical characteristics and cost data of the candidate power plants are presented in Table 10.

4.3. Descriptions of case studies

The generation expansion planning is divided into three cases: the BAU or the BIRP case, the energy conservation or the EIRP case, and the combination of energy conservation and renewable energy options or the REIRP case. In the first case, only the supply-side options are considered in order to meet the forecasted demand while in the latter two cases the reduction of demand due to energy conservation programs is introduced.

In the BIRP case, only the conventional candidate power plants are considered to meet the future demand. The candidate power plants include coal- and oil-fired steam plants, gas-based combined-cycle plants, and diesel gas-turbine plants. In the EIRP case, the annual peak demand is deducted due to the implementation of the energy conservation programs in the transport, industrial and residential sectors. The supply-side options in this case consider only the conventional candidate plants. In the REIRP case, both the renewable energy options, including biomass and solar energy, and energy conservation programs are simultaneously combined.

5. Results and discussions on energy demand and energy saving

5.1. Results of the BAU scenario

In the BAU scenario, results from the LEAP model reveal that the total energy demand is estimated to be about 39 724 thousand toe and 88 319 thousand toe in 2000 and 2020, respectively, as presented in Table 11. The energy requirement in 2020 is more than two times the energy demand in 2000. In the transport sector, which focused only on the road transportation, the energy demand is estimated at 15 408 thousand toe and 48 043 thousand toe in 2000 and 2020, respectively. In 2000, the requirement of diesel is estimated to be about 65% of the total energy

Table 10
Technical characteristics and cost data of the candidate power plants used in analysis

Plant type	Fuel type	Capacity (MW)	Heat rate (MJ/kWh)	Capital cost[a] (10^6 US$)
Conventional options				
Oil-fired plant	Fuel oil	1000	8.99	574.57
		700	9.04	415.47
		300	9.55	212.46
Coal-fired plant	Coal	1000	9.49	652.36
		700	9.55	469.93
		300	10.16	240.01
Gas turbine plant	Diesel	200	11.71	69.82
		100	12.43	39.50
Combined cycle plant	Natural gas	700	7.04	280.00
		300	7.55	138.25
Clean options				
Biomass-based plant	Fuel wood	100	9.95	147.64
Solar power plant	–	1	–	2.75

Source: Ref. [17].
[a] Constant prices at 2000.

Table 11
Estimated energy demand by economic sectors under different scenarios

Scenario/sector	Energy demand (thousand toe)					
	2000	2003	2005	2010	2015	2020
BAU scenario	39 724	46 493	50 601	60 540	70 379	88 319
Residential sector						
–Electricity demand	1761	2032	2220	2597	3003	3298
–Non-electricity demand	5814	6155	6369	6578	6875	6742
Industrial sector						
–Electricity demand	3347	3657	3880	4498	5214	6044
–Non-electricity demand	13 394	14 636	15 527	18 001	20 868	24 191
Transport sector						
–Diesel	9960	12 600	14 126	17 831	21 073	28 800
–Gasoline	5238	7172	8219	10 736	13 019	18 893
–LPG	208	237	257	298	326	348
–Electricity	3	3	3	3	3	3
EEI scenario	39 724	46 435	50 502	60 540	70 379	88 212
Residential sector						
–Electricity demand	1761	2028	2212	2586	2990	3284
–Non-electricity demand	5814	6102	6279	6486	6782	6654
Industrial sector						
–Electricity demand	3347	3657	3879	4497	5212	6039
–Non-electricity demand	13 394	14 636	15 527	18 001	20 868	24 191
Transport sector						
–Diesel	9960	12 600	14 126	17 831	21 073	28 800
–Gasoline	5238	7172	8219	10 736	13 019	18 893
–LPG	208	237	257	298	326	348
–Electricity	3	3	3	3	3	3

(*continued on next page*)

Table 11 (*continued*)

Scenario/sector	Energy demand (thousand toe)					
	2000	2003	2005	2010	2015	2020
PTI Scenario	39 724	46 302	50 362	60 143	69 860	87 685
Residential sector						
–Electricity demand	1761	2032	2220	2597	3003	3298
–Non-electricity demand	5814	6155	6369	6578	6875	6742
Industrial sector						
–Electricity demand	3347	3657	3880	4498	5214	6044
–Non-electricity demand	13 394	14 636	15 527	18 001	20 868	24 191
Transport sector						
–Diesel	9960	12 598	14 123	17 826	21 067	28 792
–Gasoline	5238	6982	7980	10 338	12 499	18 256
–LPG	208	237	257	298	326	348
–Electricity	3	5	5	8	9	12
FEI scenario	39 724	46 413	50 440	60 302	70 070	87 822
Residential sector						
–Electricity demand	1761	2032	2220	2597	3003	3298
–Non-electricity demand	5814	6155	6369	6578	6875	6742
Industrial sector						
–Electricity demand	3347	3657	3880	4498	5214	6044
–Non-electricity demand	13 394	14 636	15 527	18 001	20 868	24 191
Transport sector						
–Diesel	9960	12 559	14 042	17 709	20 916	28 558
–Gasoline	5238	7134	8141	10 621	12 867	18 637
–LPG	208	237	257	298	326	348
–Electricity	3	3	3	3	3	3

requirement in this sector and is expected to decline to 60% in 2020. The share of LPG demand decreases from 1.35% to 0.72%, while the share of gasoline is expected to increase from 34% to 39%. In the industrial sector, the projected demand increases from 16 741 thousand toe to 30 236 thousand toe. The projected energy requirement in the residential sector increases from 7575 thousand toe in 2000 to 10 040 thousand toe in 2020. The proportion of electricity demand in this sector gradually increases from 23.24% in 2000 to 32.85% in 2020. Although the proportions of non-electricity demand comprising charcoal, fuel wood and LPG gradually decreases, the LPG demand is expected to increase from 12.46% in 2000 to 19.81% in 2020.

In addition, the CO_2 and other harmful emissions are estimated by using the emission factors in the TED of the LEAP model. The CO_2 emissions in terms of CO_2 equivalent (CO_{2eq}) are increased by 132 534 thousand tons in 2020 which is higher than two times the CO_{2eq} in 2000 (Fig. 2.). The NO_x and SO_2 emissions in 2020 are estimated to be approximately 631 thousand tons and 397 thousand tons which are higher than those in 2000 by approximately three times and two times, respectively (see Table 12).

5.2. Scenarios analysis

The EEI scenario, which emphasizes the efficiency improvement of electric and non-electric appliances in the residential and industrial sectors, can reduce not only the energy requirement but also the environmental emissions. Results show that an overall energy saving and reduction of CO_2 emissions in 2020 are approximately 107 thousand toe and 39 thousand tons of CO_{2eq}, respectively, when compared to the BAU scenario (see Table 11). The reduction of electricity demand is estimated

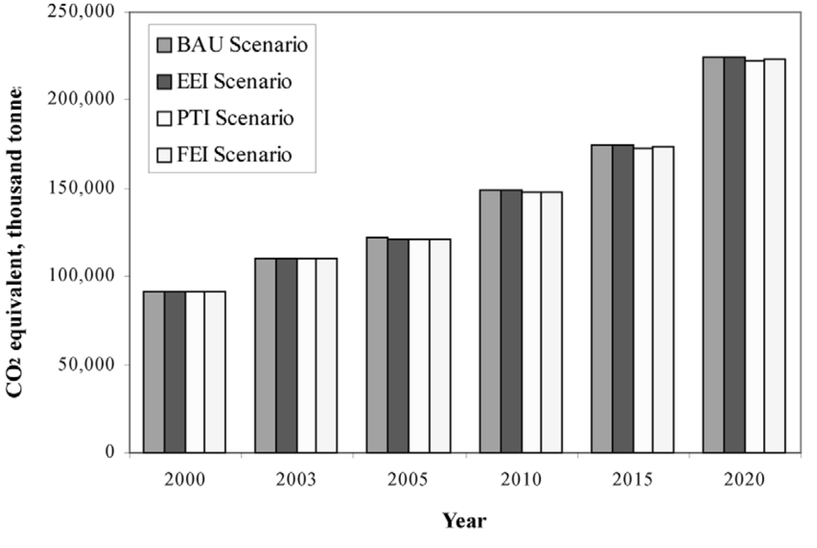


Fig. 2. Projection of CO_2 emissions under different scenarios.

Table 12
Estimated other environmental emissions under different scenarios

Scenario	Estimated environmental emissions (10^3 ton)					
	2000	2003	2005	2010	2015	2020
BAU scenario						
–NO_x	247.8	300.4	331.7	409.2	481.8	631.50
–SO_2	220.8	241.1	255.6	295.9	342.4	396.8
–TSP	24.5	25.2	25.5	25.1	25.1	23.5
EEI scenario						
–NO_x	247.8	300.4	331.7	409.2	481.8	631.50
–SO_2	220.8	241.1	255.6	295.9	342.4	396.8
–TSP	24.5	25	25.1	24.7	24.7	23.2
PTI scenario						
–NO_x	247.8	299.4	330.4	407.1	479.1	628.30
–SO_2	220.8	241.1	255.6	295.9	342.4	396.8
–TSP	24.5	25.2	25.5	25.1	25.1	23.5
FEI scenario						
–NO_x	247.8	299.7	330.2	407.1	479.1	627.20
–SO_2	220.8	241.1	255.6	295.9	342.4	396.8
–TSP	24.5	25.2	25.5	25.1	25.1	23.5

to be 18% of the overall energy saving and 82% for non-electricity demand. Most non-electricity savings come from the implementation of efficient cooking stoves in the residential sector. Also, the reduction of electricity demand is mainly from the implementation of efficient appliances in the residential sector which accounts for 13% of the total energy saving.

The PTI scenario, which increases public transportation systems, especially the MRT and BTS projects, could further reduce energy requirements and environmental emissions. While the electricity requirement is increased by 9 thousand toe due to the extension of MRT and BTS projects, the gasoline and diesel demand is decreased by 637 and 7 thousand toe, respectively, in 2020 compared to the BAU scenario. As a result, overall energy saving and reduction of CO_2 emissions in 2020 are estimated to be about 635 thousand toe and 2024 thousand tons of CO_{2eq}. In addition, NO_x emission is estimated to reduce by approximately 3.2 thousand tons in 2020.

In the FEI scenario, which emphasizes the fuel economy improvement in passenger cars, the gasoline and diesel requirement could be reduced by 256 and 242 thousand toe and CO_2 emissions could be mitigated by 1560 thousand tons of CO_{2eq} in 2020 compared to the BAU scenario. Moreover, NO_x emission can be reduced by 4.3 thousand tons in 2020.

The results of scenarios show that it is possible to reduce energy demand by 0.12%, 0.72% and 0.57% of total energy consumption in 2020 through the implementation of efficient appliances in the residential and industrial sectors (EEI scenario), the improvement of public transportation (PTI scenario) and the increase in fuel economy of passenger cars (FEI scenario), respectively. The corresponding figures in the mitigation of CO_2 emission are expected to be 0.02%, 0.91% and 0.70% of total CO_{2eq} in 2020. If all scenarios are simultaneously implemented, the potential of energy saving and CO_2 mitigation in 2020 are 1241 thousand toe and 3623 thousand tons CO_{2eq}, respectively. Also, NO_x emission is mitigated by 7.5 thousand tons in 2020. The mitigation of environmental emission is mainly from the reduction of non-electricity demand.

6. Impacts on power generation expansion plan

Results of the least-cost plans from the IRP model reveal that the introduction of the energy conservation programs and renewable energy options could affect the installed capacity, energy generation, generation mix and environmental emissions e.g., CO_2, SO_2 and NO_x emissions. Also, the total cost of electricity generation could be affected through these implementations. The reduction of electricity demand through the energy conservation programs results in less installed capacity, electricity generation and environmental emissions, particularly CO_2 emission. The implementation of renewable power plants, which is considered as zero CO_2 emission, reduces the share of coal-based generation; therefore, the CO_2 emission can be reduced as well. In addition, other emissions such as SO_2 and NO_x are also diminished. The reduction of electricity generation reduces both the investment cost and fuel cost. As a result, the total costs including capital and operating and maintenance costs would be decreased.

Table 13
Generating capacity by plant types in 2020

Case study	Generating capacity (MW)							Total capacity (MW)
	Hydro	Coal-fired	Oil-fired	CC	GT	IPP	Biomass	
BIRP	2886	32 900	2970	11 900	168	5244	–	53 182
EIRP	2886	31 900	3270	11 900	268	5244	–	52 582
REIRP	2886	32 500	2 970	11 600	168	5244	100	52 582

In the BIRP case, the total additional capacity and total electricity generation during the planning horizon are estimated to be 46 846 MW and 3983 TWh, respectively. The coal-based plants take the highest proportion in total installed capacity and electricity generation in all cases followed by the generation of the gas-based and oil-based plants, respectively. In the EIRP case, the total installed generation capacity is estimated to decrease by 600 MW, compared to the BIRP case, as well as in the REIRP case (see Table 13). Also, the cumulative generation reduction through the energy conservation programs during 2003–2020 is evaluated to be about 38 442 GWh in both the EIRP and REIRP cases (see Table 14).

The profile of electricity generation would also change after the implementation of both the energy conservation programs and the renewable energy options. The generation share of coal-based plants decreases from 35.99% in the BIRP case to 35.23% in the EIRP case and to 35.09% in the REIRP case, as presented in Table 14. In the REIRP case, approximately 1426 GWh of electricity is generated from biomass-based plants, whereas no electricity is generated from the solar-energy plant due to its high capital cost. According to the change in generation-mix, the fuel-mix and fuel requirement would be different in each case. Total fuel requirement in the EIRP and REIRP cases is estimated to be less than that in the BIRP case by 8180 thousand toe and 7629 thousand toe, respectively.

The reduction in environmental emissions such as CO_2, SO_2 and NO_x emissions can take place either by the change in electricity requirements in terms of generation

Table 14
Generation-mix by plant types during the planning period

Case study	Electricity generation (TWh)							Total (TWh)
	Hydro	Coal-fired	Oil-fired	CC	GT	IPP	Biomass	
BIRP	75	1433	319	1403	39	714	–	3983
EIRP	75	1389	321	1405	40	715	–	3945
REIRP	75	1384	319	1411	39	715	2	3945

Table 15
Estimated emission during 2003–2020

Case study	CO_2 (10^6 ton)	SO_2 (10^3 ton)	NO_x (10^3 ton)
BIRP	2895	4774	10 873
EIRP	2857	4768	10 751
REIRP	2852	4766	10 740

reduction, which also decreases fuel requirements, called demand-side effect or the change in electricity generation-mix and fuel-mix, called supply-side effect [18]. In both EIRP and REIRP scenarios, the emissions can be reduced through not only the supply-side effect but also the demand-side effect. Table 15 presents cumulative CO_2, SO_2 and NO_x emissions in the planning horizon. In the EIRP case, total CO_2 emission in the planning horizon is found to be less than that in the BIRP case by 38 299 thousand tons. Also, in the REIRP case the CO_2 emission is estimated to mitigate by 42 762 thousand tons compared to the BIRP case. The CO_2 emission in the REIRP case can be mitigated higher than that in the EIRP case when compared to the BIRP case. This is due to the preeminence of supply-side effect. In the REIRP case, the biomass-based plants, which are considered as net zero CO_2 emission, would be introduced and also selected in the plan. Apart from the mitigation of CO_2 emission, other emissions such as SO_2 and NO_x emissions are also diminished. In the EIRP and REIRP cases, the cumulative SO_2 and NO_x emissions during the planning period are estimated to mitigate by 5.60 thousand tons and 122.23 thousand tons, and by 8.20 thousand tons and 133.11 thousand tons, respectively.

Total costs of electricity generation in all cases are presented in Table 16. Total expenditures, including capital and operating and maintenance (O&M) costs in the EIRP and REIRP cases, are evaluated to reduce by US$ 411 million and US$ 424 million, respectively, compared to the BIRP case. Although the capital cost in the REIRP case is higher than the cost in the EIRP case, the fuel and O&M costs are estimated to be less than those in the EIRP case, resulting in lower total costs of electricity generation in the REIRP case (see Table 16).

Table 16
Cumulative costs during the planning horizon

Case study	Cost components (10^6 US$)			LRAC[a] (cents/kWh)
	Capital	O&M	Total cost	
BIRP	5940	37 780	43 720	3.32
EIRP	5789	37 520	43 309	3.32
REIRP	5790	37 506	43 296	3.32

[a] LRAC stands for long run average cost.

7. Conclusions and recommendations

The assessment of energy demand along with the environmental emissions can help the energy planner to develop an energy plan in a sustainable manner. The scenario analysis reveals that the implementation of public transportation systems has a high potential to reduce both energy requirements and CO_2 emissions, followed by the improvement of fuel economy in passenger cars and the energy efficiency improvement of appliances. The highest potential of energy savings and mitigation of CO_2 emission in 2020 are expected to be 1240 thousand toe and 3622 thousand tons, respectively, if all strategies are simultaneously implemented. In this study, however, the penetration rate of efficient appliances, especially efficient motors in the industrial sector, is assumed to be at a very low rate. Because most efficient motors utilized in Thai industrial sector have been imported [15], their capital cost is too high compared to the conventional motors. However, electric motors are the main electricity-consuming devices used in the industrial sector. If efficient motors are promoted, the electricity consumption in this sector will decrease. In order to promote the efficient motor, the financial support should be considered and others barriers should be studied in depth.

Further study includes the implementation of the energy conservation strategies and biomass utilization for reducing primary energy requirement and mitigating CO_2 emission and other harmful emissions such as SO_2 and NO_x from the power sector. Because the reduction of electricity demand results in less energy requirement in the power generation which contribute to less environmental emissions, and the biomass utilization with plantation is considered as net zero CO_2 emission. Since Thailand is an agriculture-based country, the wastes from agricultural activities such as rice husk and bagasse can be utilized as energy sources to produce both heat and power. Therefore, not only the imported fossil energy but also the environmental emissions, particularly greenhouse gas emission, can be reduced through energy conservation activities and biomass utilization.

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